Assessing decadal changes in the Deep Western Boundary Current absolute transport southeast of Cape Farewell, Greenland, from hydrography and altimetry

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[1] In earlier studies, the decadal variability of the Deep Western Boundary Current (DWBC) transport in the vicinity of Cape Farewell, Greenland, has been assessed from changes in the baroclinic velocities computed from hydrographic data and referenced to 1000 m depth. The main limitation of using such an estimate as an index for the DWBC absolute transport variability comes from the unaccounted for decadal velocity changes at the reference level (1000 m). These changes may substantially contribute to the DWBC absolute transport variability by compensating for or adding to the baroclinic transport changes. To assess this contribution to variability, we quantify the decadal velocity changes which occurred at 1000 m depth southeast of Cape Farewell since the mid-1990s. The analysis combines estimates of the baroclinic velocity changes in the water column derived from repeat hydrography at ~59.5°N and the velocity changes at the sea surface derived from altimetry. An increase in the southward velocity at 1000 m above the DWBC between the periods of 1994–1997 and 2000–2007 is inferred. It indicates that the increase in the DWBC absolute transport was larger than the 2 Sv (1 Sv = 10^6 m^3 s^{-1}) increase in its baroclinic component referenced to 1000 m. This result and the observed coherence of the DWBC absolute and baroclinic transport changes between individual observations imply that the DWBC absolute transport variability in the region is underestimated but qualitatively well represented by its baroclinic component on decadal and shorter time scales.

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1. Introduction

[2] The Deep Western Boundary Current (DWBC) carries the Nordic-overflow-derived deep waters through the northern North Atlantic to lower latitudes. The DWBC is the main contribution to the lower limb of the Atlantic meridional overturning circulation, and hence is a key component of the Earth's climate system. For this reason, the decadal variability of the DWBC has recently been the subject of increased attention [e.g., *Bacon*, 1998, hereinafter B98; *Kieke and Rhein*, 2006; *Dickson et al.*, 2008; *Bacon and Saunders*, 2010; *Sarafanov et al.*, 2009, hereinafter S09].

[3] Available records based on continuous direct current measurements [e.g., *Dickson et al.*, 2008; *Bacon and Saunders*, 2010] are not long enough to reliably assess the DWBC transport variability on a decadal time scale. However, in the absence of data on absolute flow velocities, temporal changes in the DWBC transport have been estimated from changes in the baroclinic geostrophic velocities derived from repeat hydrography and referenced to intermediate levels in the water column [see B98; *Kieke and Rhein*, 2006; S09].

[4] In the vicinity of Cape Farewell (Figure 1a), the DWBC baroclinic transport referenced to 1000 m depth has fluctuated since the 1950s by ±2–2.5 Sv (1 Sv = 10^6 m^3 s^{-1}) around the 5.5 Sv long-term (1950s to 2000s) mean (S09). The transport was low in the 1950s, high in the late 1970s to early 1980s, and extremely low in the early 1990s to mid-1990s (B98). Since the mid-1990s, the DWBC baroclinic transport increased by ~2 Sv and thereby restored to a moderate-to-high state (S09). In these estimates, the DWBC was defined as the part of the western boundary current carrying waters denser than σ_0 = 27.80; the same definition is used in the present study.

[5] The main issue related to the interpretation of the baroclinic transport variability as an "index" (B98) for the variability of the absolute transport is the unaccounted contribution of the absolute velocity changes at the refer-

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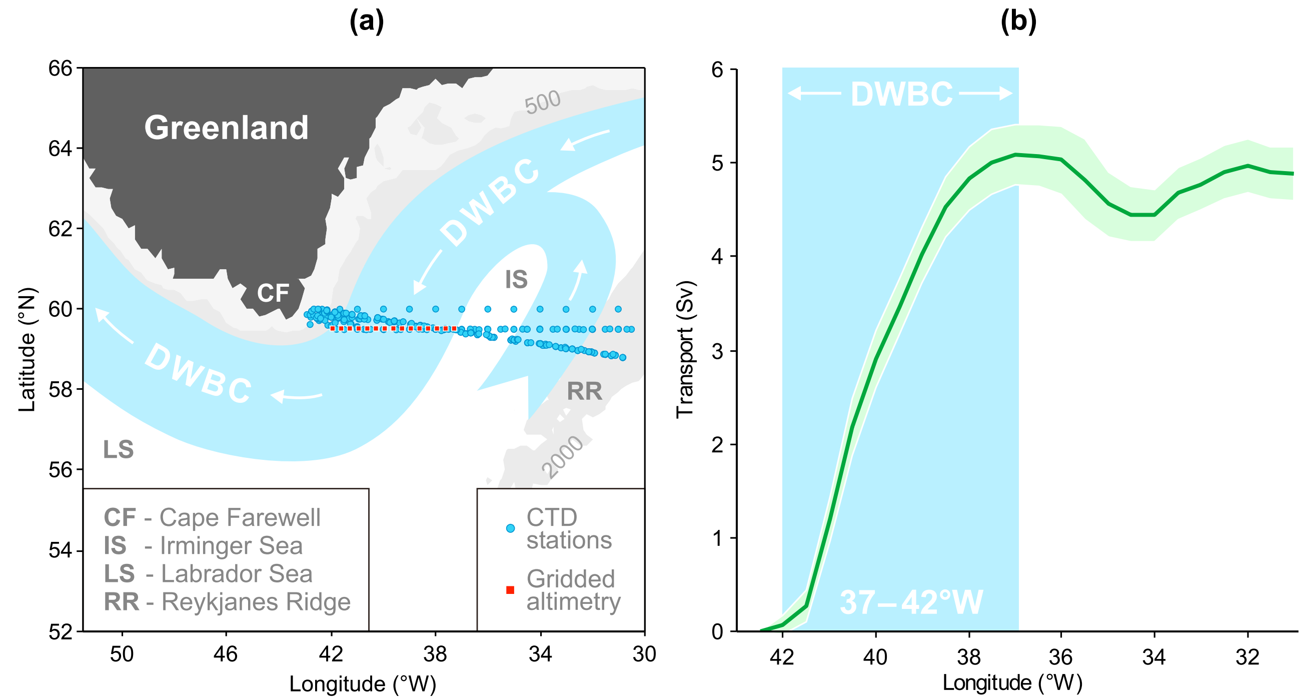

Figure 1. (a) Locations of the 18 CTD sections (59°N–60°N, 1991–2007) across the DWBC and the weekly altimetry data (1992–2007) grid points above the DWBC (~59.5°N, 37°W–42°W) in the southern Irminger Sea. Table 1 lists the hydrographic cruises. (b) The 1991–2007 mean zonally accumulated baroclinic transport (referenced to 1000 m depth) of the deep waters (σ_0 > 27.80), indicating a mean southward DWBC baroclinic flow of ~5 Sv within the 37°W–42°W longitude range and a weak northward baroclinic flow east of 37°W. The mean transport is computed using the estimates by S09 (see Figure 1b in S09). The light green envelope in Figure 1b shows the standard errors (uncertainties) of the means.

ence level. These changes, being “hidden to hydrography” [*Dickson et al.*, 2008], cannot be assessed unless additional information is available. For the DWBC at Cape Farewell, nearly a half of the absolute transport is unaccounted for by the baroclinic transport referenced to 1000 m [e.g., *Holliday et al.*, 2009]. The unaccounted transport variability associated with velocity changes at the reference level may therefore substantially contribute to the variability of the DWBC absolute transport by either compensating for or adding to the baroclinic transport changes. Using baroclinic-transport decadal changes as an index for decadal changes in the absolute transport is thus strongly limited by the assumption that velocities at the reference level either do not substantially fluctuate on a decadal time scale or fluctuate coherently with the referenced velocities of the deep water flow. This is not necessarily so, especially since the mid-1990s, when the increase in the DWBC baroclinic transport was accompanied by a weakening of the subpolar gyre [*Häkkinen and Rhines*, 2004, 2009]. There are indications that the decline of the sea surface circulation evidently documented from altimetry data might have locally affected the intermediate levels [*Häkkinen and Rhines*, 2004]. In the Irminger Sea, the East Greenland/Irminger Current (the northern limb of the gyre), which flows southwestward above the DWBC, weakened at the surface [see *Häkkinen and Rhines,* 2004, Figure 2]. If the gyre weakening “penetrated” down to the intermediate layer, the southwestward velocities at 1000 m depth, used as a reference level by B98 and S09, have declined since the mid-1990s, thereby compensating for the increase in the DWBC transport referenced to this level.

[6] The aim of this study is to examine whether this compensation occurred or the DWBC absolute transport in the southwestern Irminger Sea has increased since the mid-1990s, as suggested by the 2 Sv increase in the DWBC baroclinic transport referenced to 1000 m (S09). This examination will be done by quantifying the velocity changes at 1000 m above the DWBC southeast of Cape Farewell between the mid-1990s (1994–1997) and the 2000s (2000–2007). The sign and magnitude of these changes will, if significant, quantify the DWBC transport change that is unaccounted for by the baroclinic transport estimates of S09.

[7] To perform this analysis, data on actual velocity variability at some depth in the water column are required along with hydrography-derived velocity shears. Although there are no sufficiently long mooring records for the region, velocity variability at the sea surface has been available since 1992 from satellite altimetry.

[8] The idea is to “extract” the unknown velocity changes at the reference level from changes in both the altimetry-derived sea surface velocities and the velocity shears derived from hydrographic data. More specifically, we assess the mid-1990s to 2000s velocity changes at 1000 m depth above the DWBC at ~59.5°N, 37°W–42°W (Figure 1) as the difference between changes in the sea surface velocities derived from altimetry and changes in the sea surface

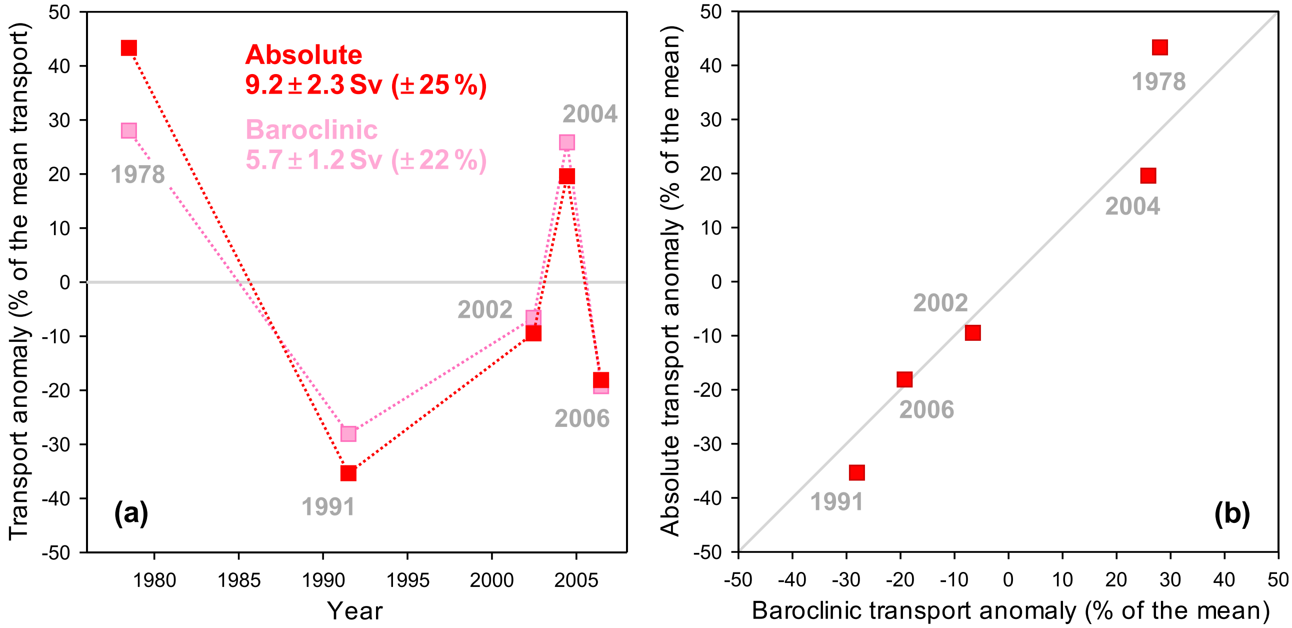

Figure 2. (a) The 1978–2006 anomalies of the DWBC absolute and baroclinic transports southeast of Cape Farwell, as obtained from hydrographic observations combined with direct current measurements for the absolute transports. Anomalies are given in percent of the means as calculated from the five transport values: 9.2 Sv for the DWBC absolute transport and 5.7 Sv for the baroclinic one. Based on the values reported by B98 (1978 and 1991) and S09 (2002–2006); baroclinic transports are referenced to 1000 m depth. The 2002–2006 absolute transport values were obtained with a least squares inverse model that uses direct current measurements to adjust the hydrography-derived baroclinic velocity profiles [see *Lherminier et al.*, 2007]. (b) The 1978–2006 DWBC absolute and baroclinic transport anomalies shown in Figure 2a plotted against each other.

baroclinic velocities (referenced to zero at 1000 m) computed from the hydrographic data used earlier by S09. The results are discussed in the general context of whether the DWBC baroclinic transport variability is a suitable index for the DWBC absolute transport variability at Cape Farewell.

2. Observed Coherence of the DWBC Baroclinic and Absolute Transport Changes

[9] A few arguments supporting the suggestion that the baroclinic transport (T_{BC}) variability is representative for the absolute transport (T_{ABS}) variability for the DWBC at Cape Farewell have been put forward (B98, S09). On the basis of the absolute and baroclinic transport estimates from two surveys carried out in April 1978 (R/V *Hudson*) and August 1991 (R/V *Charles Darwin*), B98 concluded that both the absolute and baroclinic transports of the DWBC evidently decreased between the two observations. Similarly, S09 reported on the coherent behaviors of the DWBC T_{ABS} and T_{BC} between the three occupations of the Ovide section (2002, 2004, and 2006).

[10] The qualitative consistency of the DWBC T_{ABS} and T_{BC} variability between the above five individual observations (1978, 1991, 2002, 2004, and 2006) is evident from Figure 2, where the 1978–2006 DWBC T_{ABS} and T_{BC} anomalies are shown as a percent of the corresponding mean transport values. Quantitatively for the five observations, the mean DWBC T_{BC} (5.7 Sv, close to the 5.5 Sv estimated by S09 for the 1950s to 2000s mean T_{BC}) constitutes ~60% of the mean T_{ABS} (9.2 Sv). The T_{BC} variability measured by the standard deviation from the mean (1.2 Sv) accounts for half (52%) of the T_{ABS} variability (2.3 Sv). The DWBC T_{ABS} and T_{BC} relative changes (±25% and ±22% of the mean T_{ABS} and T_{BC}, respectively) are close to each other.

[11] The fact that the observed DWBC T_{ABS} changes are of the same sign but on average twice as large as the T_{BC} changes means that the DWBC transport changes caused by velocity changes at the reference level (1000 m) add to the T_{BC} changes and do not compensate for them. This means that the changes in the mean (averaged across the DWBC) velocity at 1000 m depth above the DWBC are of the same sign and about the same magnitude as the changes in the DWBC mean (averaged over the current) baroclinic velocity referenced to 1000 m.

[12] Though the above arguments apply for the observed transport variability shown in Figure 2, they cannot be extrapolated with confidence to the transport changes on a decadal time scale (i.e., to the decadal trends). Indeed, one cannot exclude the possibility that, while showing similar changes between consecutive synoptic states, T_{ABS} and T_{BC} have different long-term behaviors. The decadal signals reported for the DWBC T_{BC} at Cape Farewell (B98, S09) might be a feature of the T_{BC} only if compensated for by an "opposite" decadal variability of the velocity at the reference level. This compensation might appear unlikely, particularly given the apparent consistency of the observed T_{ABS} and

Table 1. Hydrographic Cruises

Month and Year	Research Vessel	Cruise
Aug 1991	*Charles Darwin*	62
Sep 1991	*Meteor*	18
Sep 1992	*Valdivia*	129
Nov 1994	*Meteor*	30
Jun 1995	*Valdivia*	152
Sep 1996	*Valdivia*	162/2
Oct 1997	*Professor Shtokman*	36
Oct 2000	*Pelagia*	169
Jun 2002	*Thalassa*	Ovide-02
Aug 2002	*Akademik Mstislav Keldysh*	48
Sep 2003	*Pelagia*	216
Jun 2004	*Akademik Ioffe*	15
Jun 2004	*Thalassa*	Ovide-04
Jun 2005	*Akademik Ioffe*	18
Sep 2005	*Pelagia*	240
Jun 2006	*Maria S. Merian*	Ovide-06
Jul 2006	*Akademik Ioffe*	21
Jul 2007	*Akademik Ioffe*	23

T_{BC} changes, but, once again, it cannot be discarded without careful examination. Below we examine the probability of such a compensation for the case of the DWBC T_{BC} increase since the mid-1990s (S09) using altimetry data, which allow us to extend the comparison of the DWBC T_{BC} and T_{ABS} changes to the decadal time scale.

3. Data and Method

[13] Data of two types are used in this study: (1) shipboard, full-depth conductivity-temperature-depth (CTD) casts and (2) satellite altimetry measurements. The CTD data collected in 1991–2007 in the southern Irminger Sea are from nearly colocated repeat sections running from Cape Farewell eastward and crossing the DWBC at ~59.5°N: the A1E line (1991–1997), the 59.5°N–60°N section (1997–2007), the Ovide section (2002–2006), and the AR7E section occupied on board the R/V *Pelagia* (2000–2005) (see Figure 1a and Table 1). This set of CTD sections is the same as in S09, except for the omission of the R/V *Discovery* section (August 1997) because of its different location and orientation (slanted section in Figure 1a by S09). The altimetry data are the 1992–2007 sea surface height anomalies from the weekly AVISO 1/3° gridded topography.

[14] On the basis of the CTD data, the full depth profiles of the baroclinic velocity (geostrophic velocities adjusted to zero at 1000 m depth) for each pair of adjacent stations were computed for all sections. The 59.5°N–60°N repeat section is strictly zonal and thus the geostrophic velocities obtained from these data represent the meridional velocity component. The other sections, being designed to cross the Greenland slope and the boundary currents at nearly a right angle, are slanted clockwise from the zonal direction by ~10° ($\pi/18$). Since the boundary currents in the region have a westward component (i.e., the currents are not strictly meridional), geostrophic velocities derived from the slanted sections are assumed to be somewhat higher, on average, than velocities in the zonal sections. Therefore, to make the velocities derived from the slanted sections thoroughly comparable with those derived from the 59.5°N–60°N data (i.e., to extract the meridional velocity component), the former were multiplied by cos ($\pi/18$) = 0.985, i.e., reduced by 1.5%. Note that this "tiny" correction for the section orientation is negligible compared to the uncertainties discussed below and the correction does not significantly influence the results.

[15] On the basis of AVISO weekly sea surface height anomaly data, the meridional sea surface velocity anomalies at ~59.5°N above the DWBC (37°W–42°W, Figure 1) were computed. As we are interested in the velocity changes over time, no information on the mean sea surface velocities (from the mean topography) is required.

[16] The decadal (mid-1990s to 2000s) changes in the meridional velocity at the reference level (1000 m) above the DWBC were estimated in accordance with a simple approach. The flow speed at the sea surface v_{SS} at some location can be formally decomposed into the relative velocity at the sea surface v_{BC} referenced to some subsurface level and the velocity at the reference level v_0 at this location: $v_{SS} = v_{BC} + v_0$. Accordingly, the time rate of change in velocity at the sea surface (dv_{SS}/dt) can be represented as the sum of the changes in the baroclinic velocity at the sea surface (dv_{BC}/dt) and in velocity at the reference level (dv_0/dt): $dv_{SS}/dt = dv_{BC}/dt + dv_0/dt$.

[17] This decomposition allows us to obtain the unknown velocity change at the reference level (dv_0/dt) from the known velocity changes at the sea surface (dv_{SS}/dt and dv_{BC}/dt):

$$dv_0/dt = dv_{SS}/dt - dv_{BC}/dt. \quad (1)$$

In our particular case, v is the meridional velocity component, dv_0/dt is the sought velocity change at the reference level (1000 m), dv_{SS}/dt is the altimetry-derived sea surface velocity change, and dv_{BC}/dt is the change in the hydrography-derived sea surface velocity referenced to 1000 m. Thus, in accord with the decomposition equation (1), we can quantify the velocity change at the reference level as the difference between the altimetry- and hydrography-derived sea surface velocity changes at the same longitude over the same time period.

[18] Unless otherwise stated, we focus on the 1994–2007 period. In S09, we obtained the DWBC T_{BC} 2 Sv increase as the difference between the mean DWBC T_{BC} for the 2000s and mid-1990s. Given the strong short-term variability in the T_{BC} time series in the 2000s, this estimate appeared to be the most robust in a statistical sense. Therefore, in the present study we keep the same two reference time periods for the velocity averaging over time and assess the velocity changes as the differences between the 2000–2007 and 1994–1997 means. For the zonally averaged velocities we also quantify the 1994–2007 trends. To obtain the most robust decadal signal in the altimetry-derived sea surface velocity anomalies, we use the entire set of weekly altimetry data in all estimates. Exclusion of part of the data, e.g., winter months, does not lead to any significant change in the altimetry-derived velocity changes.

[19] Figure 3 shows the 1991–2007 changes in the DWBC baroclinic transport, its cross-sectional area, and its average baroclinic velocity referenced to 1000 m depth. Figure 4 displays the vertical distribution of hydrography-derived changes in the baroclinic velocities at ~59.5°N, 37°W–42°W between the mid-1990s and 2000s. Figure 5 shows the zonal distributions of velocity changes at the sea surface between

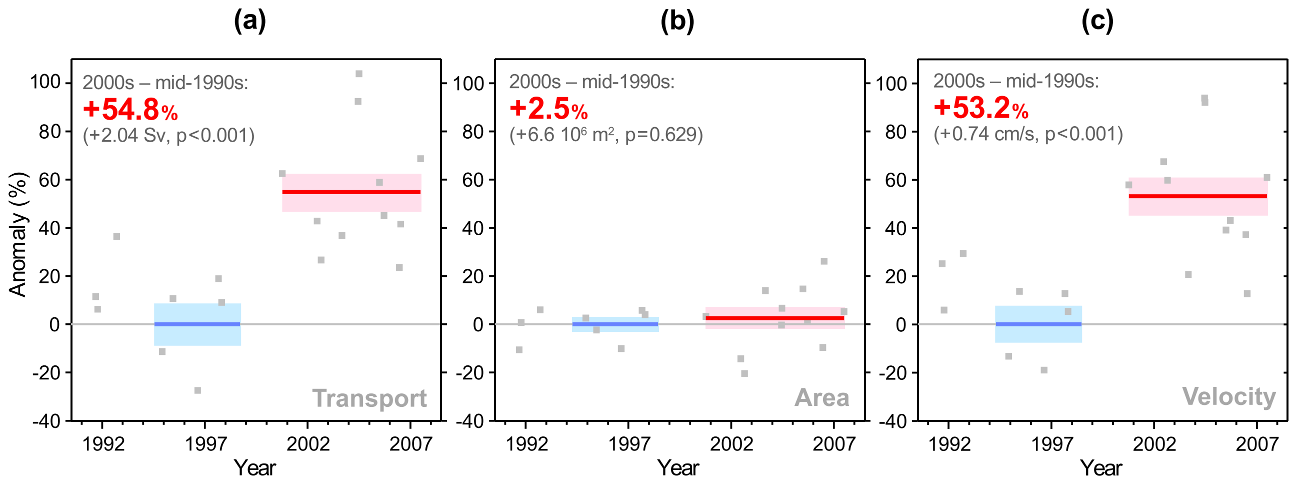

Figure 3. The 1991–2007 anomalies of the DWBC (a) baroclinic transport (referenced to 1000 m depth), (b) cross-sectional area and (c) average baroclinic velocity. Based on the estimates reported by S09 (see Figure 2a of S09). Anomalies are percentages of the corresponding 1994–1997 mean values, so that the mean anomaly for the mid-1990s is equal to zero. The average DWBC baroclinic velocity for each section was obtained by dividing the DWBC baroclinic transport in the section by the DWBC cross-sectional area. The mean anomalies for the mid-1990s (1994–1997) and 2000s (2000–2007) periods are plotted as blue and red lines, respectively. The light blue and pink shaded bars indicate ±1 standard error of the mean. The variable p is the Student's t test based probability that the obtained differences between the means are due to chance alone (i.e., the "null" hypothesis is that the differences are actually zero).

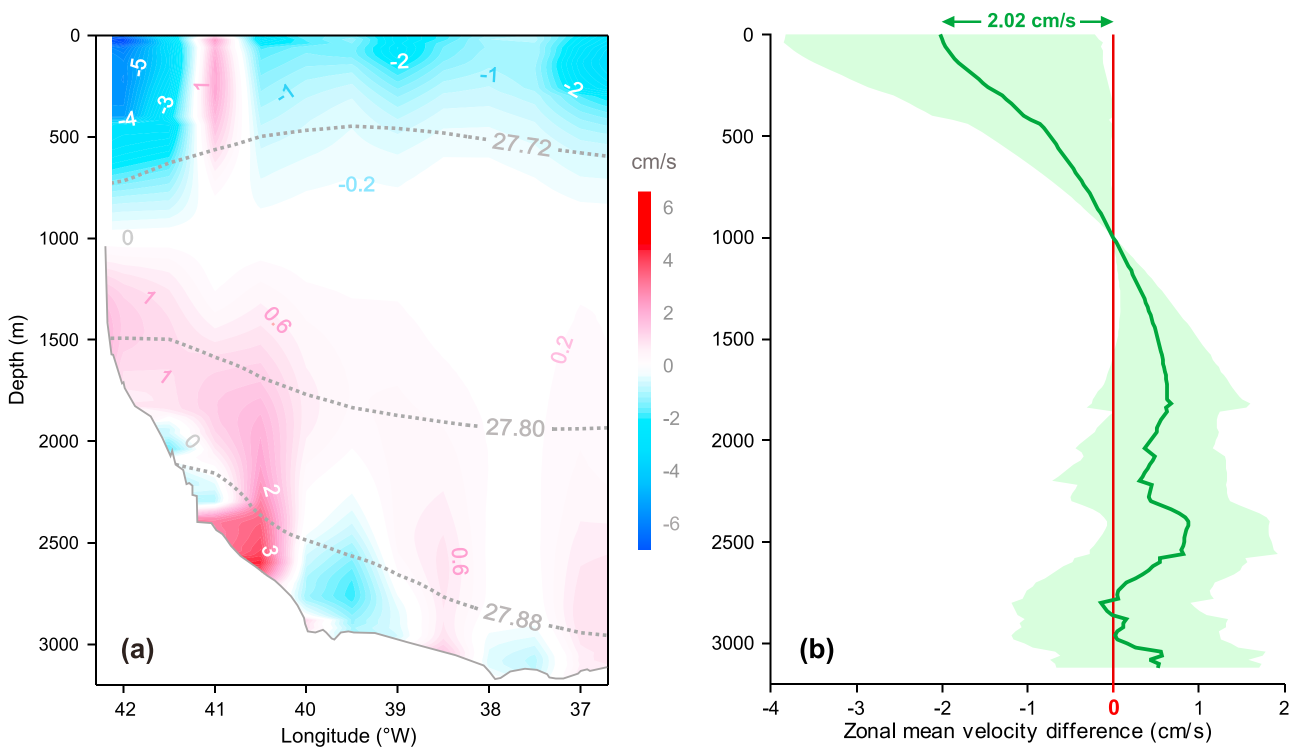

Figure 4. (a) The differences between the 2000s (2000–2007) and mid-1990s (1994–1997) means of the baroclinic velocities (cm s^{-1}) referenced to 1000 m depth in the Irminger Sea for the DWBC longitudinal range (37°W–42°W) at ~59.5°N. Positive values indicate stronger southward flow. The gray dotted lines denote the 1994–2007 mean positions of the isopycnals separating the water mass density classes: the Labrador Sea Water (27.72 < σ_0 < 27.80), Iceland-Scotland Overflow-derived Water (27.80 < σ_0 < 27.88) and Denmark Strait Overflow Water (σ_0 > 27.88). (b) Vertical distribution of the zonally averaged differences shown in Figure 4a (green curve) and their mean uncertainties (light green shading).

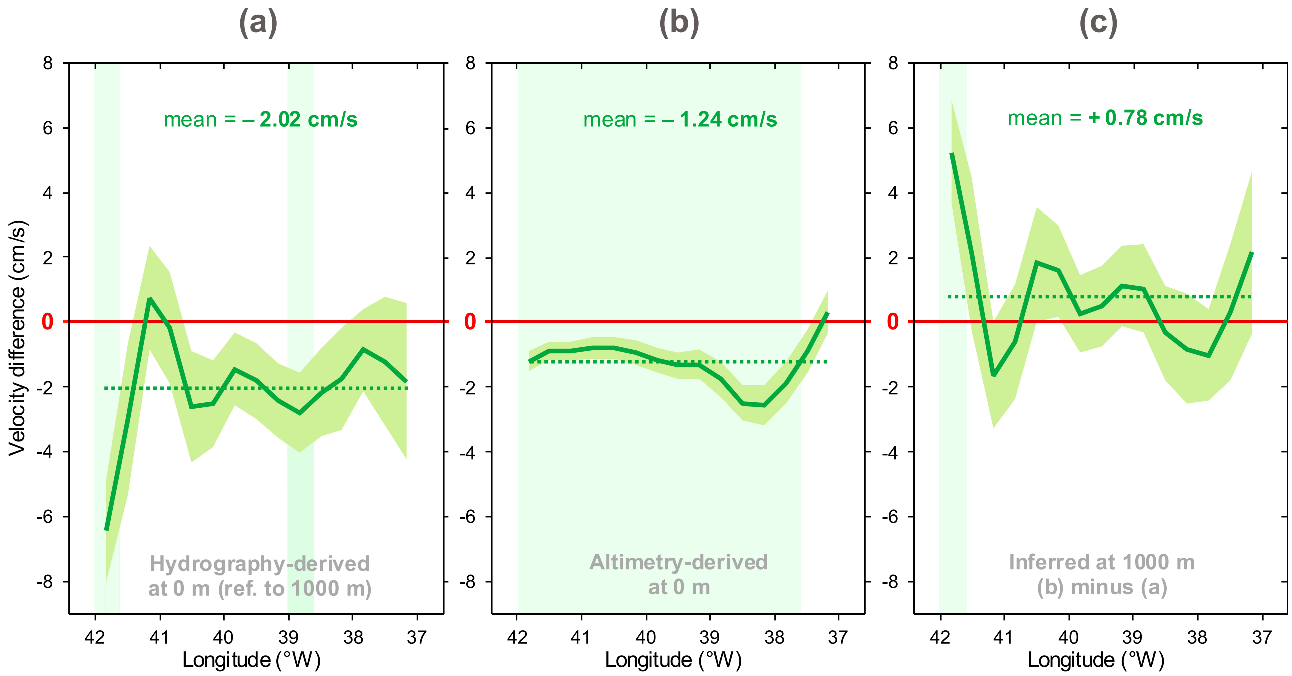

Figure 5. The differences between the 2000s (2000–2007) and mid-1990s (1994–1997) means of the meridional velocity (v, cm s^{-1}) at ~59.5°N in the Irminger Sea as a function of longitude for (a) the sea surface hydrography-derived baroclinic v referenced to 1000 m, (b) the altimetry-derived geostrophic v, and (c) v at 1000 m obtained in line with the decomposition equation (1). Positive differences indicate "southward" increments of v. The standard errors of the differences at each longitude are the green shadings. The light green vertical stripes mark longitudes where the differences are statistically nonzero at the 95% confidence level. Dashed horizontal lines denote the zonal mean values.

the mid-1990s and 2000s, as derived from hydrography and altimetry, along with the inferred velocity changes at 1000 m depth in the DWBC longitudinal range (37°W–42°W, Figure 1b). Figure 6 displays the time series of the sea surface velocity anomalies, zonally averaged over the 37°W–42°W range, and the inferred change in the zonal mean velocity at 1000 m. (The sign convention is that positive velocities are southward.)

[20] When averaging over time, the uncertainties (standard errors) σ_m of the mean values are determined as $\sigma_m = \sigma/\sqrt{N-1}$, where σ is the standard deviation and N is the number of statistically independent observations. The hydrographic sections are repeated (bi-) annually, and the hydrography-derived time series show no significant autocorrelation. So, those observations are independent in a statistical sense. The integral time scale estimated for the altimetry-derived meridional v anomalies at individual longitudes between 37°W and 42°W at ~59.5°N is very close to 1.0 weeks, in agreement with direct current measurements in the region. Indeed, a current meter mooring deployed at 59.65°N, 41.80°W shows integral time scales of ~7 days at 200 m depth (N. Daniault, personal communication, 2009). For the altimetry-derived v anomalies zonally averaged over the 37°W–42°W range, the integral time scale is 3.2 weeks. Accordingly, for the hydrographic data and altimetry-derived v anomalies at individual longitudes, N is equal to the sample size; for the zonally averaged altimetry-derived v anomalies, N is obtained by dividing the number of weekly values by 3.2.

[21] Uncertainties in the differences between the means are obtained as the square root of the sum of the squared standard errors of the means. The statistical significances of the magnitudes (Figures 3 and 5) and signs (Figure 6) of the differences and trends were assessed using a Student's t test. The hypotheses tested in each case are defined in captions for Figures 3, 5, and 6.

4. Increase in the DWBC Baroclinic Velocity Since the mid-1990s

[22] Following B98 and *Kieke and Rhein* [2006], in S09 we have defined the DWBC as the southwestward flow of deep waters denser than $\sigma_0 = 27.80$. To estimate the DWBC T_{BC}, a zonal integration was performed from the East Greenland slope to the middle of the Irminger Basin (~37°W at ~59.5°N). On average, this zonal integration limit corresponds to the maximum of the zonally accumulated T_{BC} in the $\sigma_0 > 27.80$ layer (Figure 1b). In all cases, baroclinic eddies at the eastern integration limit (~37°W) were entirely included or excluded (see the method section by B98 for details). At such definition, the DWBC T_{BC} may change because of changes (1) in the baroclinic velocities referenced to zero at 1000 m and (2) in the area of the DWBC stratum intersected by the sections. Therefore, it is essential to examine whether and to what extent the DWBC T_{BC} increase between the mid-1990s and 2000s (+2 Sv, S09) was associated with an increase in the baroclinic velocities of the deep water flow or with an increase in the DWBC area (i.e., in the volumes of waters ascribed to the DWBC).

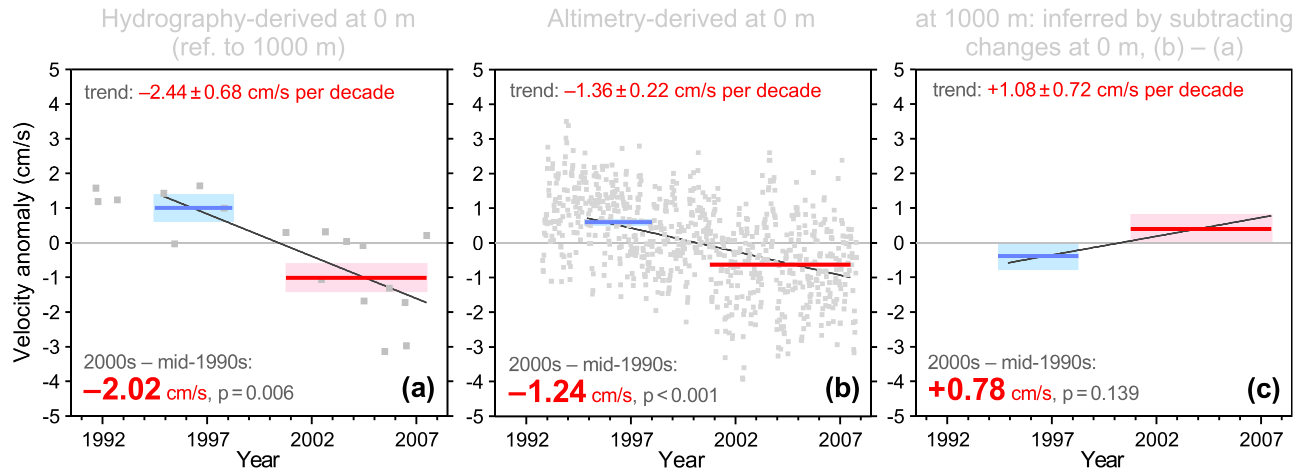

Figure 6. (a) The 1991–2007 anomalies in the zonal mean sea surface meridional velocity (v, cm s^{-1}) referenced to 1000 m depth as derived from the hydrographic data for the 37°W–42°W longitudinal range at ~59.5°N. (b) The 1992–2007 zonal mean sea surface v anomalies derived from the altimetry data. (c) The change in the zonal mean v at 1000 m depth obtained in line with the decomposition equation (1). In Figures 6a and 6b, the mean v anomalies for the mid-1990s (1994–1997), 2000s (2000–2007), and the 1994–2007 trends are plotted as blue, red, and black lines, respectively; the light blue and pink bars indicate ±1 standard error of the mean. In Figure 6c, the inferred v change at 1000 m and the associated uncertainties are visualized with the same color convention as in Figures 6a and 6b. The variable p is the Student's t test based probability that the actual velocity changes between the mid-1990s and 2000s have signs opposite to the obtained ones.

[23] Figure 3 shows that the DWBC T_{BC} increase (+55% of the mean T_{BC} for the mid-1990s) occurred almost solely because of the increase in the mean DWBC baroclinic velocity (+53%), while the DWBC cross-sectional area did not significantly change (+2.5%, significant at less than a 40% level). The mean baroclinic velocity of the DWBC increased between the mid-1990s (1994–1997) and 2000s (2000–2007) by 0.74 cm s^{-1}; this increase, as well as the resulting DWBC transport increase of 2 Sv reported by S09, is significant at the 99.9% confidence level.

[24] The increase in the DWBC baroclinic velocity is also evident from the differences in the baroclinic velocities at ~59.5°N (Figure 4). The zonal mean change in the baroclinic velocity profiles (Figure 4b) shows generally stronger southward baroclinic flow below the reference level (1000 m) in the 2000s. It is noteworthy that the distribution of the velocity differences in the boundary current (Figure 4a) is barely significant, as the differences are close to or less than the associated uncertainties (Figure 4b). The increase in the mean baroclinic velocity of the DWBC is nonetheless highly significant (Figure 3c), as the signal-to-noise ratio for the velocity averaged over the density and longitudinal ranges of the DWBC ($\sigma_0 > 27.80$, ~37°W–42°W) is much higher than at any particular location in the DWBC.

5. Velocity Changes Above the DWBC

5.1. Zonal Distribution

[25] Estimating the mid-1990s to 2000s change in the DWBC transport that is unaccounted for by the baroclinic transport analysis of S09 requires quantification of the zonal distribution of the velocity changes at the reference level.

[26] Figure 5 displays the zonal distributions of velocity changes at the sea surface and those at the 1000 m depth obtained in line with the decomposition equation (1). Figures 5a and 5b show that both the altimetry-derived velocities and the hydrography-derived baroclinic velocities at the sea surface have decreased since the mid-1990s, consistent with the decline of the subpolar gyre strength [*Häkkinen and Rhines*, 2004]. The average magnitude of the altimetry-derived velocity decrease (–1.24 cm s^{-1}, Figure 5b) is close to that of the 1992–2002 sea surface velocity trend for this location, as reported by *Häkkinen and Rhines* [2004, Figure 2]. The decrease in the hydrography-derived baroclinic sea surface velocities (Figure 5a) is larger than that obtained from the altimetry data (Figure 5b) for most of the longitudinal range, indicating that the velocity change at the reference level above the DWBC is generally positive (i.e., southward). On average, the southward velocity at 1000 m increased by 0.78 cm s^{-1} (Figure 5c).

[27] However, unlike the altimetry-derived velocity changes, the hydrography-derived velocity changes and the inferred changes at the reference level are not significant at the 95% confidence level, except at ~42°W and ~39°W at the sea surface and ~42°W at 1000 m (Figures 5a and 5c). The two peaks in the zonal distribution of the hydrography-derived velocity changes, at ~41°W and ~42°W (Figure 5a), result primarily from eddy-like structures in two of the four sections in the mid-1990s (1994 R/V *Meteor* and 1997 R/V *Professor Shtokman*), i.e., the peaks can be attributed to a strong local variability affecting the 1994–1997 mean velocity structure. Similar eddy-related signals in the weekly altimetry data are effectively filtered by averaging over time, resulting in the robust smooth pattern of differences between the 2000s and mid-1990s (Figure 5b).

[28] The velocity changes at the reference level at individual longitudes (Figure 5c) are, on average, significant only at the 59% level. Thus, the effort to obtain the zonal

distribution of velocity changes at 1000 m depth above the DWBC is not successful. This is not surprising, as the magnitude of the long-term velocity change ("signal") at the intermediate depths at any particular longitude was expected to be low compared to the short-term upper ocean variability ("noise").

[29] The problem of the low significance of the obtained result cannot be solved by "increasing" the magnitude of the referenced velocity changes at the sea surface by means of choosing a deeper reference level. Figure 4b shows that at 1500 m, the deepest reference level that can reasonably be chosen for the DWBC, the zonal mean baroclinic velocity increment is +0.5 cm s^{-1}, with a mean uncertainty of ±0.5 cm s^{-1}. If the 1500 m depth is chosen as a reference level, the decrease in the hydrography-derived referenced velocities at the sea surface will be −2.5 cm s^{-1}, and the resulting velocity increase at the reference level (+1.3 cm s^{-1}) will be, on average, significant at the ~66% level. Thus, no intermediate level exists at which zonal distribution of the mid-1990s to 2000s velocity changes would be significant.

[30] It is also noteworthy that the problem cannot be feasibly solved by increasing the number of hydrographic sections used in the analysis. The uncertainties (standard errors) of the velocity changes at the reference level (Figure 5c) are, on average, roughly 2 times larger than the magnitudes of these changes. The errors result primarily from the high uncertainties in the sea surface baroclinic velocity changes derived from the hydrographic data (Figure 5a). Therefore, the mean standard error of the hydrography-derived sea surface velocity changes would have to be reduced by at least a factor of 4 to obtain a velocity change at 1000 m which is significant at the 95% level. Consequently, ~16 times as many hydrographic sections would be needed (as the error is inversely related to the square root of the observation number), assuming that the standard deviation of the sea surface velocities will not substantially decrease with the increase in the number of sections used. In other words, the hydrographic measurements would have to be carried out every 2–3 weeks. Direct current measurements in each cruise and mooring deployment are certainly a better solution.

5.2. Changes in the Zonal Mean Velocities

[31] More robust estimates can be derived for the changes in the zonally averaged velocities above the DWBC. Passing to the zonal mean values, we reduce the "noise," thereby increasing the significance of the estimates, but lose the (barely significant) information on the zonal structure of the velocity changes needed to strictly quantify the DWBC transport change associated with the velocity changes at the reference level.

[32] The time series of the zonally averaged altimetry- and hydrography-derived surface velocity anomalies and the inferred 2000s to mid-1990s difference and 1994–2007 trend in the average velocity at 1000 m above the DWBC are shown in Figure 6. Unlike the zonal distribution of the baroclinic velocity changes (Figure 5a), the decrease in the zonally averaged baroclinic velocities at the sea surface (−2.02 cm s^{-1}, Figure 6a) is significant at the 99% confidence level. The sea surface velocity decrease derived from altimetry (−1.24 cm s^{-1}, Figure 6b) is significant at the 99.9% level.

[33] The "resulting" zonal mean velocity change at 1000 m depth between the mid-1990s and 2000s (+0.78 cm s^{-1}, Figure 6c) is significantly positive at the 86.1% confidence level. The inferred 1994–2007 velocity trend at 1000 m (+1.08 ± 0.7 cm s^{-1} per decade) is significantly positive at the 93% level. As noted in section 3, we prefer to rely on the results obtained from the differences between the 2000s and mid-1990s means (rather than on the trends), in order to be consistent with S09. The 86.1% level is lower than the usually defined lowest appropriate level of confidence (90%), but the probability that the velocity at 1000 m decreased is only 13.9%. Consequently, the DWBC transport increase since the mid-1990s associated with the velocity change at the reference level is 6.2 times more probable than its decrease.

[34] As shown in section 4, the 2 Sv increase in the DWBC baroclinic transport (referenced to 1000 m) which occurred between the mid-1990s and 2000s was due to an increase of 0.74 cm s^{-1} in the southward baroclinic velocity averaged over the DWBC. A decrease of the southward velocity of the same magnitude at the reference level (1000 m) would compensate for the increase in the DWBC baroclinic transport. There is a probability of 97.1% that either the average southward velocity at 1000 m increased or the velocity decrease at 1000 m was less than 0.74 cm s^{-1}. Hence, the probability that the DWBC absolute transport *did* increase is 97.1%.

[35] Since the DWBC stratum (σ_0 > 27.80) thickness varies with longitude (it increases eastward from zero at ~42°W to more than 1000 m at ~37°W, see Figure 4a), the DWBC transport change associated with velocity changes at the reference level depends strongly on the zonal distribution of these changes. Therefore, in the absence of statistically reliable information on this distribution, it is impossible to quantify the DWBC transport increase associated with the inferred change in the reference velocity. It is, however, interesting to speculate on its probable magnitude. This magnitude ranges between +1.3 Sv and +2.2 Sv; the lower value is obtained on the assumption that the zonal distribution of velocity changes at 1000 m (+0.78 cm s^{-1} on average) is as shown in Figure 5c, and the higher value is obtained on the assumption that the velocity change at 1000 m is evenly distributed above the DWBC. Given the DWBC baroclinic transport increase of 2 Sv, the net ("baroclinic" plus "barotropic") change in the DWBC transport in the southern Irminger Sea between the mid-1990s and 2000s might be somewhere around +3–4 Sv. We emphasize that the assumptions made do not allow this range to be treated otherwise than as a very tentative one.

6. Longer-Term Changes in the DWBC Transport, 1980s to 2000s

[36] Using the altimetry data, we inferred the increase in the average southward velocity at 1000 m depth above the DWBC and hence the consistency of the DWBC baroclinic and absolute transport changes southeast of Cape Farewell between the mid-1990s and 2000s. The absence of pre-1990s long-term sea level measurements from space limits our ability to examine the robustness of the relationship between the decadal changes in the DWBC baroclinic and absolute transports for the earlier decades. Although the estimates of the pre-1990s changes in the DWBC absolute

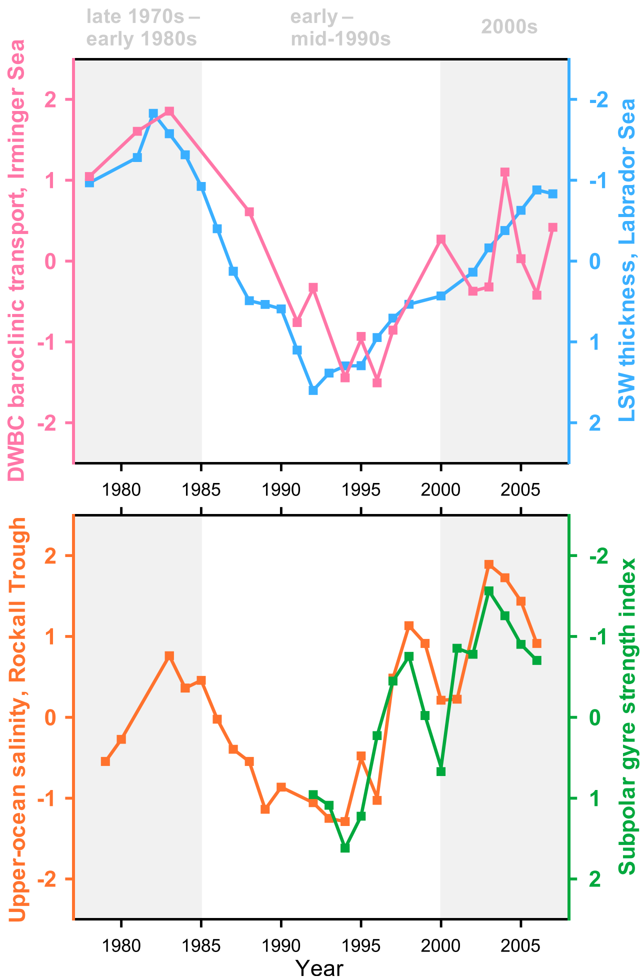

Figure 7. Anomalies of the DWBC baroclinic transport at Cape Farewell (pink), after B98 and S09; LSW layer ($34.62 \leq \sigma_{1.5} \leq 34.72$) thickness in the Labrador Sea interior (blue), a proxy of the convection intensity [after *Curry et al.* [1998; S09]; the upper ocean (0–800 m) salinity in the Rockall Trough (orange) [after *Holliday et al.,* 2008]; the first principal component of the altimetry-derived sea surface heights in the northern North Atlantic (green), an index of the subpolar gyre strength [after *Häkkinen and Rhines,* 2009]. The anomalies are converted to a common dimensionless scale by normalizing by their standard deviations. Note the reversed right axes. The time periods characterized by a reduced LSW thickness, high DWBC baroclinic transport, weak subpolar gyre, and increased salinity in the Rockall Trough are shaded gray.

transport are hindered by the lack of data, one argument for the existence of the decadal signal in these changes (predicted by the baroclinic transport variability) can be put forward.

[37] As demonstrated in S09, the DWBC baroclinic transport in the Irminger Sea is negatively correlated with thickness of the Labrador Sea Water (LSW) in the Labrador Sea: a proxy of the LSW production rate. The DWBC transport increase since the mid-1990s was associated with the decrease in the LSW production. At the same time, the subpolar gyre weakened and contracted, and this is also thought to be associated with the decrease in the LSW production, which is one of the drivers for the cyclonic gyre circulation [e.g., *Bersch et al.*, 2007; *Häkkinen and Rhines*, 2004]. Weakening and contraction of the gyre, in turn, resulted in the rapid salinity increase at the upper-ocean and intermediate levels in the Iceland basin and Rockall Trough [*Bersch et al.*, 2007; *Holliday et al.*, 2008; *Thierry et al.*, 2008; *Sarafanov et al.*, 2008]. Conversely, the DWBC baroclinic transport decrease between the early 1980s and early 1990s to mid-1990s was accompanied by the increase in the LSW production and decrease in the upper-ocean salinity in the Rockall Trough (an indication of the subpolar gyre eastward expansion, as discussed by *Bersch* [2002]).

[38] The described coherent changes are illustrated in Figure 7 by the time series of anomalies of the DWBC baroclinic transport (B98, S09), LSW thickness (S09), upper-ocean salinity in the Rockall Trough [*Holliday et al.*, 2008], and the subpolar gyre strength index by *Häkkinen and Rhines* [2004]. It is noteworthy that the gyre index and salinity in the Rockall Trough show consistent behavior even on an interannual time scale. In general, Figure 7 suggests that the four phenomena: decadal changes in the (1) intensity of deep convection in the Labrador Sea, (2) strength and zonal extension of the subpolar gyre, (3) upper-ocean hydrographic conditions in the northeast North Atlantic, and (4) DWBC transport, are linked, representing a complex coherent oceanic response to the decadal variability of the surface forcing.

[39] This apparent linkage deserves a dedicated investigation that is beyond the scope of this paper. We suggest that the coherence in the above changes is an indication, though tentative and indirect, of the existence of a pronounced decadal signal in the DWBC absolute transport variability since the late 1970s, as the proxy (or at least the constituent) of this signal, the decadal variability of the baroclinic transport, fits changes observed in reality. In other words, if the decadal variability of the DWBC baroclinic transport at Cape Farewell is qualitatively representative of the DWBC absolute transport changes (as inferred herein for the 1994–2007 period), the latter would be consistent with the general pattern of the recent decadal hydrographic and circulation changes in the northern North Atlantic.

7. Conclusion

[40] The 2 Sv increase in the DWBC baroclinic transport referenced to 1000 m depth reported by S09 together with the present estimates of the velocity changes at this depth allow us to conclude that the DWBC absolute transport at Cape Farewell has almost certainly increased since the mid-1990s (1994–1997). We find an 86% probability that the southward velocity at 1000 m above the DWBC was stronger in the 2000s (2000–2007) than in the mid-1990s (on average by +0.78 cm s^{-1}) and hence the probability that the DWBC transport increased by more than 2 Sv (S09) is ~6 times higher than the probability that the transport increase was less than 2 Sv.

[41] The most important result, significant at the 97% level, is that the DWBC absolute transport *did* increase after the 1994–1997 period, as was suggested by the baroclinic transport analysis. Consequently, the decline of the upper-ocean circulation in the northern North Atlantic since the

mid-1990s [*Häkkinen and Rhines*, 2004] was likely to be accompanied by an increase in the western boundary current transport at deeper levels, as inferred herein for the southwestern Irminger Sea. This inference agrees with an increase in the alongshore velocities at ~1500 m in the southern Labrador Sea between the second half of the 1900s and the first half of the 2000s, as observed with moored current meters [*Dengler et al.*, 2006].

[42] The mid-1990s to 2000s increase in the DWBC baroclinic and absolute transports imply that the variability of the baroclinic transport referenced to 1000 m depth is a suitable index for the DWBC absolute transport variability southeast of Cape Farewell. Indeed, the transport change in the water column associated with the mid-1990s to 2000s velocity increase at the reference level, 1000 m, adds to (and does not compensate for) the 2 Sv increase in the DWBC baroclinic transport reported by S09. The increase in the average southward velocity at 1000 m (0.78 cm s^{-1}) is close in magnitude to the increase in the DWBC baroclinic velocity referenced to 1000 m (0.74 cm s^{-1}). This implies that the baroclinic transport variability (B98, S09) underestimates but qualitatively well represents the DWBC absolute transport variability southeast of Cape Farewell on a decadal scale, as we demonstrated herein for the 1994–2007 time period. At shorter time scales, the regional variability of the DWBC absolute transport is also likely to be qualitatively well represented by its baroclinic component, as indicated by the coherence of the absolute and baroclinic transport changes between the individual observations (section 2).

[43] The question of whether the DWBC transport at Cape Farewell fluctuated before the 1990s in the manner predicted by the baroclinic transport estimates (B98, S09) remains open. Despite the apparent consistency of the DWBC transport variability inferred from hydrography alone with the recent decadal changes in the northern North Atlantic discussed in section 6, no answer can be given with confidence in the absence of pre-1990s long-term velocity measurements in the region. The answer is also unlikely to be derived in the near future from numerical simulations, as the contemporary models do not realistically reproduce the DWBC (see, e.g., section 4.5 by *Bacon and Saunders* [2010]). This highlights the great value of the moored current meter records [*Bacon and Saunders*, 2010], repeat shipboard hydrographic and velocity measurements [e.g., *Lherminier et al.*, 2007], and satellite observations [e.g., *Häkkinen and Rhines*, 2004], all of which are the indispensable complementary sources of the data for future research in this field.

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